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EXPERIMENTAL STUDIES

Three-Dimensional Reconstruction of Color Doppler Flow Convergence Regions and Regurgitant Jets: An In Vitro Quantitative Study

TAKAHIRO SHIOTA, MD, PHD, BRIAN SINCLAIR, MD, MASAHIRO ISHII, MD, XIAODONG ZHOU, MD, SHUPING GE, MD, DAG E. TEIEN, MD, MORTEZA GHARIB, PHD, DAVID J. SAHN, MD, FACC

Portland, Oregon

Objectives. This study sought to investigate the applicability of a current implementation of a three-dimensional echocardiographic reconstruction method for color Doppler flow convergence and regurgitant jet imaging.

Background. Evaluation of regurgitant flow events, such as flow convergences or regurgitant jets, using two-dimensional imaging ultrasound color flow Doppler systems may not be robust enough to characterize these spatially complex events.

Methods. We studied two in vitro models using steady flow to optimize results. In the first constant-flow model, two different orifices were each mounted to produce flow convergences and free jets—a circular orifice and a rectangular orifice with orifice area of 0.24 cm^2. In another flow model, steady flows through a circular orifice were directed toward a curved surrounding wall to produce wall adherent jets. Video composite data of color Doppler flow images from both free jet and wall jet models were reconstructed and analyzed after computer-controlled 180° rotational acquisition using a TomTec computer.

Results. For the free jet model there was an excellent relation between actual flow rates and three-dimensional regurgitant jet volumes for both circular and rectangular orifices ($r = 0.99$ and $r = 0.98$, respectively). However, the rectangular orifice produced larger jet volumes than the circular orifice, even at the same flow rates ($p < 0.0001$). Calculated flow rates by the hemispheric model using one axial measurement of the flow convergence isovelocity surface from two-dimensional color flow images underestimated actual flow rate by 35% for the circular orifice and by 44% for the rectangular orifice, whereas a hemielliptic method implemented using three axial measurements of the flow convergence zone derived using three-dimensional reconstruction correlated well with and underestimated actual flow rate to a lesser degree (22% for the circular orifice, 32% for the rectangular orifice). In the wall jet model, the jets were flattened against and spread along the wall and had reduced regurgitant jet volumes compared with free jets ($p < 0.01$).

Conclusions. Three-dimensional reconstruction of flow imaged by color Doppler may add quantitative spatial information to aid computation methods that have been used for evaluating valvular regurgitation, especially where they relate to complex geometric flow events.

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The diagnosis and quantitation of valvular insufficiency has been important as a goal for the clinical noninvasive evaluation of patients with valvular heart disease using color Doppler echocardiography. The color Doppler jet area planimetry method has been widely used for grading the severity of valvular regurgitation (1–4). However, many factors, such as instrument settings and jet eccentricity, have been suggested as altering the color Doppler-imaged jet area (5–12). More recently, laminar acceleration flow phenomena for flows toward the regurgitant orifice (i.e., flow convergence phenomena) detected more reproducibly by color Doppler flow mapping methods have been studied clinically and experimentally for (semi) quantifying the regurgitant flow rate (13–22). As yet, there has been no widely accepted noninvasive method capable of reliable quantitation, partly because evaluation of regurgitant flow events using a two-dimensional imaging system may not be robust enough to characterize these spatially complex, often asymmetric events (7,9–12,15,22).

Three-dimensional reconstruction of cardiac structures, such as coronary arteries, the mitral valve and septal defects, has been undertaken using a variety of noninvasive imaging modalities, including magnetic resonance imaging (MRI) and intravascular, transesophageal and transthoracic ultrasound imaging (23–36). However, except for the most recently developed MRI methods, three-dimensional reconstruction and quantification of the regurgitant flow events, such as flow

From the Oregon Health Sciences University, The Clinical Care Center for Congenital Heart Disease, Portland, Oregon. This work was supported by Grant HL 43287 from the National Heart, Lung, and Blood Institute, National Institutes of Health, Bethesda, Maryland.

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Address for correspondence: Dr. David J. Sahn, Director, The Clinical Care Center for Congenital Heart Disease, UHN60, Oregon Health Sciences University, Portland, Oregon 97201-3098.

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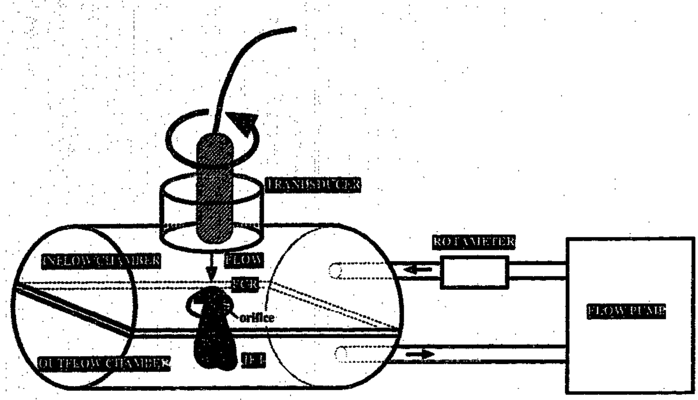

Figure 1. Free jet flow model consisting of two chambers (inflow and outflow) separated by a flat disk (12 mm thick), at the center of which a modeled orifice was inserted. At the **top** of the model, above the mounted orifice, the echocardiographic transducer could be rotated 180° on a round, flat echocardiographic window made of thin transparent plastic (1 mm). This model was connected to a steady flow pump and a rotameter to measure the actual flow rate. FCR = flow convergence region.

convergence, has not been undertaken systematically to date, except in very preliminary clinical and in vitro studies (35,36).

The aim of our study was to investigate the feasibility and potential value of the computer-controlled three-dimensional echocardiographic reconstruction method for evaluating color Doppler flow convergence and regurgitant jet phenomena as imaged within in vitro flow models constructed to provide well characterized and strictly quantifiable flow events.

Methods

Free jet model. In the first constant-flow model characterized by a proximal (height 8 cm, length 24 cm) and distal chamber (height 8 cm, length 24 cm) constructed of transparent acrylic, two different orifices were mounted to produce free jets; a circular orifice with diameter 5.5 mm (orifice area 0.24 cm^2) and a rectangular orifice with orifice area 0.24 cm^2 with a major/minor axis ratio of 4:1. Four flow rates (20, 40, 60 and 80 ml/s) were examined. Each flow was driven into the top chamber through the orifice mounted in between the top and bottom chambers, into the bottom chamber and back out to a recirculating pump. A solution of water mixed with 1% by weight cornstarch was used as the fluid medium. Actual flow rate was measured in the model using a rotameter and was cross-checked by measuring flows collected in a graduated cylinder and timed with a stopwatch. This model has previously been described (Fig. 1) and flow within it characterized (20,21).

Echocardiography and three-dimensional reconstruction. The flow convergence toward the orifice and regurgitant jet were imaged using three different aliasing velocities (19 and 35 cm/s for imaging flow convergences and 35 and 58 cm/s for imaging regurgitant jets) using the Interspec ultrasound system (Apogee RX 400) with a 5-MHz annular array transducer (Fig. 2). The color Doppler filtering was set at 1,000 Hz. In our preliminary studies (36), we noticed the importance of instrument settings involving color Doppler flow mapping for trans-

Figure 2. Example of two-dimensional color flow imaging of flow convergence region (FCR) and regurgitant jet for the rectangular orifice. Note the specific instrument settings for gray-scale transfer to the TomTec computer.

ferring the color Doppler flow mapping data to the black-and-white video composite imaging environment of the TomTec computer. Relatively high aliasing velocities such as 58 cm/s were used for obtaining clearly imaged regurgitant jet contours. However, such high aliasing velocities resulted in three-dimensional flow convergence regions imaged too small to measure, especially for low flow rates. Thus, we selected different aliasing velocities and developed a unique zero-shifted nonvariance color map to obtain clear flow convergence surface zones and regurgitant jet images in the three-dimensional data set (Fig. 2). After computer-controlled 180° rotational acquisition with the ultrasound transducer in a motorized holding system controlled by a TomTec computer, as previously reported (35), these video composite data of color Doppler images were reconstructed and analyzed using the same TomTec system. When rotational color Doppler flow mapping data were transferred into the TomTec computer, both electrocardiographic and respiratory synchronization systems were switched off because examined flows were steady. This step avoided limitations associated with temporal gating, such as a limited number of discrete images per cycle and the potential for instability of flow from compounding this assessment, and shortened the acquisition time to 5 to 10 s for the reconstructions.

To obtain the entire projection of regurgitant jet and the flow convergence toward the orifice, an oblique "bird's-eye" view from above the orifice plane was developed.

Regurgitant jet volume measurements. The volumes of regurgitant jets were measured using parallel slices through the regurgitant jet zones distal to the orifice plane. First, we selected one end slice of the jet, and in this cut plane the first subvolume was determined by drawing the corresponding contour around it. Next, we selected the adjacent slice of the jet and performed the same measurement of this cut plane as for the first. After the second measurement, the computer system added the second subvolume to the first to obtain the sum of the two measurements. The same procedure was performed one after the other until the other end of the jet, the last slice, to obtain the total sum of the jet volume. A slice thickness of 1 mm was selected for this study.

Flow convergence isovelocity surface. Similar to the processing of the regurgitant jets imaged using color Doppler flow mapping and transferred into the TomTec computer as video composite data, the shape of the flow convergence isovelocity surfaces was three-dimensionally reconstructed from different bird's-eye view perspectives. Gray-scale grading, surface rendering, image resolution and thresholding in the TomTec computer were optimized to obtain clear isovelocity surfaces.

Three orthogonal axial distances from the flow convergence boundary to the center of the orifice (a, b, c) were measured. Then, isovelocity velocity surface areas (S) and flow rates (Q = S·V, where V = aliasing velocity) were determined using the following hemielliptic mathematical equation for flow convergence isovelocity surface area calculation (15) and compared with actual flow rates:

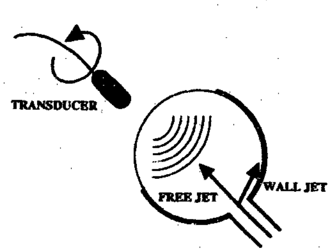

Figure 3. Diagram of free/wall jet model used in the present study.

$$S = \pi \cdot a \cdot b \cdot \left(\frac{c^2}{ab} + \varepsilon \int_0^{\phi_0} \sqrt{1 - \kappa^2 \sin^2 \phi}\, d\phi + \frac{1 - \varepsilon^2}{\varepsilon} \int_0^{\phi_0} \frac{d\phi}{\sqrt{1 - \kappa^2 \sin^2 \phi}} \right),$$

when $a > b > c > 0$,

$$\varepsilon = \sqrt{1 - \frac{c^2}{a^2}}, \quad \kappa = \sqrt{\frac{1 - (c^2/b^2)}{1 - (c^2/a^2)}}, \quad \phi_0 = \text{Arcsin} \sqrt{1 - \frac{c^2}{a^2}}.$$

The two-dimensional color flow images used as input to the TomTec computer were videotaped, and a representative plane with the clearest isovelocity surface was selected and a flow rate (Q) also calculated using a single-axis hemispheric flow convergence calculation ($Q = 2\pi r^2 \cdot V$, where r = aliasing distance; V = aliasing velocity) that is commonly used in clinical and experimental studies (14–20).

Wall jet model. To produce wall- or surface-adherent jets, we used another steady-flow model, also well characterized previously both optically and by ultrasound (12,37). Three different flows (20, 30 and 40 ml/s) through a circular orifice (area 0.15 cm^2) were driven into the "left atrial" chamber (Fig. 3). This "left atrial" model consisted of a rigid acrylic chamber equipped with a "mitral valve" regurgitant orifice in the midportion of the model. The chamber was in the shape of a cylinder 7.6 cm in diameter, 8 cm in height. The "mitral" regurgitant jet was directed centrally (free jet) or aimed toward the curved "left atrial" surrounding wall (Fig. 3). The regurgitant jet was produced by the same steady-flow pump used in the previous free jet study. A circular window made of polycarbonate in the model allowed flow imaging by Doppler echocardiography at an aliasing velocity of 58 cm/s from a site opposite the entry of the regurgitation (Fig. 3). Care was taken to align the Doppler beam toward the center of the orifice during the 180° rotational acquisition. The same three-dimensional reconstruction technique was used as for the free jet model to evaluate the propagation of the regurgitant jet (in this model, no flow convergence was imaged).

Interobserver variability. To evaluate the effect of observer variability on the measurement of three-dimensional regurgitant jet volumes and the calculated flow rates using the flow convergence method, 10 randomly selected flow condi-

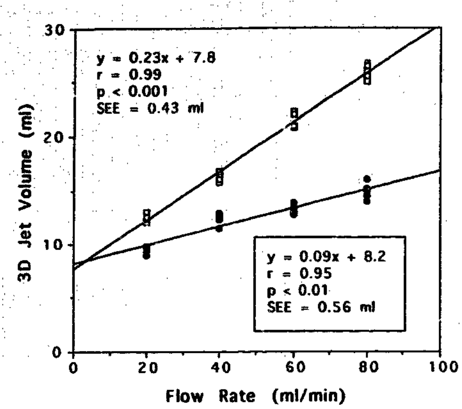

Figure 4. Linear regression analyses between actual flow rates and color Doppler regurgitant jet flow volumes calculated by three-dimensional (3D) reconstruction at an aliasing velocity of 35 cm/s. **Squares** = rectangular orifice; **circles** = circular orifice.

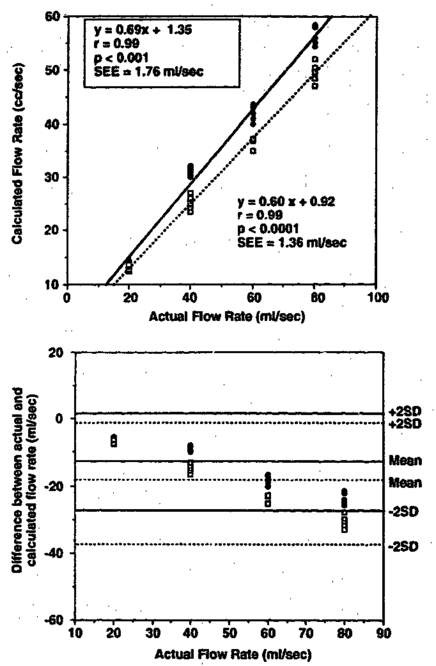

Figure 5. Linear regression **(top)** and agreement analysis **(bottom)** between calculated **(ordinate)** flow rates obtained by the three-dimensional flow convergence reconstruction at an aliasing velocity of 19 cm/s and actual flow rates **(abscissa)**. Symbols as in Figure 4.

tions were analyzed at different times with the same computer by two independent observers, each without knowledge of the results obtained by others or actual flow data.

Statistical analysis. Data are presented as mean value ± SD. For these determinations an average of five measurements each from separate three-dimensional reconstructions from raw imaging data were calculated for each flow rate. Difference in continuous variables such as jet volumes between the two different orifices were analyzed by paired t test. Correlations between continuous variable data were determined by linear regression analysis. Agreement between the actual flow rate and three-dimensional image-based calculated flow rate using the three-dimensionally reconstructed flow convergence method was tested according to the method of Bland and Altman (38) for agreement and predictability. To compare three-dimensionally reconstructed wall jet volumes with free jet volumes, the slope of the regression line for the relation of wall jet volumes to actual flow rates was compared with that for the free jet. Statistical significance was defined as $p < 0.05$.

Results

Free jet model. *Quantitative analyses of regurgitant jets.* There was an excellent relation between actual flow rates and three-dimensional regurgitant jet volumes for both circular and rectangular orifices at an aliasing velocity of 35 cm/s ($r = 0.98$ and $r = 0.99$, respectively) (Fig. 4). However, the rectangular orifice produced larger jet volumes than the circular orifice, even at the same flow rate ($p < 0.0001$) (Fig. 4). Results for each of the other aliasing velocities were similar with respect to these relations. However, the higher aliasing velocity (58 cm/s) produced smaller three-dimensional jet volumes than the lower aliasing velocity (mean 10.9 ± 2.2 vs. 12.6 ± 2.4 ml, $p < 0.001$).

Conventional two-dimensional hemispheric versus three-dimensional, three-axis flow convergence isovelocity surface method calculations of flow rate. Calculated flow rates using the conventional one-axis measurement of the flow convergence isovelocity surface area with the hemispheric assumption measured from the original videotaped two-dimensional images underestimated actual flow rate by 35 ± 12% for the circular orifice and by 44 ± 21% for the rectangular orifice at the aliasing velocity of 19 cm/s. In contrast, three-axis measurements of the flow convergence region determined from and measured on the three-dimensional reconstructions correlated well with and underestimated actual flow rates to a lesser degree (i.e., 22 ± 6.8% for the circular orifice, 32 ± 7.4% for the rectangular orifice [$r = 0.99$, SEE 1.8 ml/s, $p < 0.003$, and $r = 0.99$, SEE 0.3 ml/s, $p < 0.0001$, respectively]) (Fig. 5). Results for the other aliasing velocity (35 cm/s) were similar for the three-axis measurements with respect to the underestimation of the actual flow rate (24 ± 7.4% for the circular orifice, 34 ± 5.6% for the rectangular orifice). However, the conventional one-axis measurements with the simple hemispheric isovelocity surface assumption at this aliasing velocity again underestimated actual flow rates even more severely for both the circular and rectangular orifices (41 ± 18% and 52 ± 23%, respectively).

For the rectangular orifice, three-dimensionally rotated

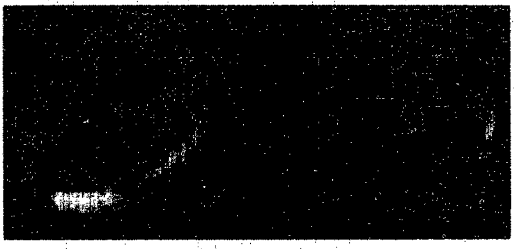

Figure 6. Three-dimensional reconstructions of flow convergence region for the rectangular (left) and circular (right) orifices. Note the elongated shape of the flow convergence toward the rectangular orifice.

views demonstrated a more elongated contour of the flow convergence surface along the major axis than the circular orifice (Fig. 6). For high flow rates and low aliasing velocity, the contour of the flow convergence isovelocity surface was more generally spherical than those at lower flow rates imaged using high aliasing velocity. The more flattened and elongated the shape of the flow convergence region, the more underestimation of the actual flow rates by the one-axis hemispheric method. In other words, the geometry of the flow convergence region observed by the three-dimensional reconstruction method was consistent with the underestimation of actual flow rates by the hemispheric assumption.

Characteristics of jet propagation for free versus wall jets. The three-dimensional reconstruction using spatially rotated views showed symmetric jet propagation for the circular orifice and asymmetric flaring jet propagation for the rectangular orifice in the first model (Fig. 7). Free jets were similar in shape when directed centrally in the second model, whereas in the setup yielding a wall jet, the jet was flattened against and spread along the wall surface, and as expected, a major alteration in regurgitant jet propagation was observed (Fig. 8).

Figure 7. Example of three-dimensional reconstruction of flow convergence region (FCR) and regurgitant jet (JET) for the rectangular orifice, showing a flaring regurgitant jet.

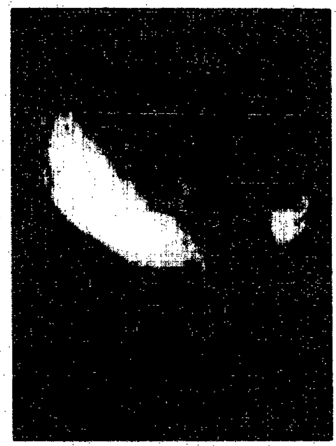

Figure 8. Three-dimensional visualization of a wall jet showing side (top) and front views (bottom) of the wall adherent jet. With conventional color Doppler two-dimensional images, it is difficult to appreciate the entire projection of this wall adherent jet.

The wall jet setting yielded statistically smaller three-dimensional jet volumes than free jets when expressed as a function of the slope of the relation of jet volumes to flow rate in the same model (regression slope 0.25 ± 0.6 for wall jet vs. 0.31 ± 0.3 for free jet, $p < 0.01$).

Interobserver variability. There was excellent agreement between the two independent observer measurements for three-dimensional regurgitant jet volumes and the calculated flow rates using the flow convergence method ($r = 0.95$, mean difference 3.5 ± 4.5 ml for the former and $r = 0.87$, mean difference 4.8 ± 4.2 ml/s for the latter).

Discussion

The methods used in the present study yielded three-dimensional ultrasound-based flow images of hydrodynamic events known to occur in valvular disease, including turbulent jet spray and flow acceleration zones, demonstrating potentially important insights for improving color flow methods used for clinical evaluation of the severity of valvular regurgitation. The present study, using computer-controlled three-dimensional reconstruction, also demonstrated a major difference in regurgitant jet propagation between free jets and wall-adherent jets.

Regurgitant jet imaging. The diagnosis and quantitation of valvular insufficiency has been important as a goal for clinical noninvasive evaluation of patients with coronary or valvular disease using Doppler echocardiography. Among the methods used clinically, the color Doppler jet area planimetry method is the simplest and has been widely used for grading the severity of valvular regurgitation, although many variables that affect the results should be taken into consideration (5–12). Using in vitro flow model, several groups, including Cape et al. (7) and our laboratory (10), have reported that flow constraint by adjacent concave surfaces induced smaller jet areas than free jets imaged by color Doppler echocardiography. Using a chronic animal model with surgically created quantifiable eccentric mitral regurgitation, we also reported (11) that the severity of regurgitation correlated poorly with the color Doppler jet area, suggesting the limited capability of this two-dimensional method for estimating the severity of mitral regurgitation, especially for eccentric regurgitation. As previously reported by Thomas et al. (6) and as observed in the present study, the projection of the valvular regurgitant jet imaged using color Doppler flow mapping depended on the orifice shape and surrounding structures. Many of the other problems that we encountered are inherent limitations in ultrasound Doppler as a method for study of disorganized flow events (5). Evaluation of regurgitant flow events using two-dimensional imaging systems may not be robust enough to characterize these complex often asymmetric events. Also it would be difficult to mentally reconstruct the image of the entire jet projection from the conventional two-dimensional color flow mapping, especially for the wall-adherent jet. In contrast, this three-dimensional reconstruction method could provide not only visualization, but also quantitative analysis of such spatially complicated flows. These major advantages should be emphasized even though quality of the images available from these three-dimensional systems still needs to be improved. Especially for in vivo or clinical flows, three-dimensional development and propagation reconstruction would be more complicated than for the in vitro flows that we studied, and the images might be of lesser quality (35,39). Three-dimensional reconstruction strategies need to be optimized, and their digital mating with the most advanced parallel-processing systems for ultrasound flow imaging still remains to be accomplished.

Three-dimensional reconstruction of flow convergence regions. Imaging of the proximal flow convergence region toward a regurgitant orifice by color Doppler flow mapping has been reported (13) to be useful for identifying the site of regurgitation and has been used for grading its severity. The flow convergence phenomenon has been examined experimentally and clinically for quantifying the regurgitant flow volume and flow rate mainly in mitral regurgitation using a variety of geometric assumptions of the isovelocity surface, most commonly that of a hemispheric isovelocity flow convergence surface (14–16). However, the shape of the color Doppler flow convergence isovelocity surface depends on many factors, including instrumentation, and physiologic factors, such as frame rate and geometry of the regurgitant valve (15–20). It is important to understand the three-dimensional contours of the isovelocity surface because the flow rate in these methods is calculated as the product of the isovelocity surface area and the aliasing velocity.

The inability of even three-dimensional ultrasound methods to give a true representation of these shapes in view of the angle dependency of Doppler interrogation is an inherent limitation. Near the edge of the flow convergence, the reconstructed isovelocity surface was derived from streamlines at an increasing angle to the direction of the Doppler interrogation. Therefore, oblique flows proceeding at an acute angle toward the orifice are at a substantial angle to the direction of ultrasound interrogation, and portions of these edge zones are thus lost from the flow convergence aliasing images. Their true shapes can only be determined by techniques that are not angle dependent (10,17) or by using additional windows for interrogation to fill in the data set lost from oblique vectors not parallel to the direction of interrogation or viscous surface effects near the orifice, or both.

Nonetheless, in the present study, the color Doppler three-dimensional method could provide the whole image of the flow convergence zone, whereas the conventional two-dimensional Doppler flow mapping provides one slice image through the flow convergence zone. For the asymmetric orifice and for low flow rates at high aliasing velocities, the three-dimensional method showed a flattened and elongated shape of the convergence zones, demonstrating a significant deviation from the shapes that would best support use of the hemispheric assumption. Such three-dimensional geometric observations were consistent with a severe underestimation of the actual flow rates by the hemispheric model with a single-axis measurement of distance to the orifice from an alias parallel to the direction of scanning. More suitable geometric surface assumptions, such as a hemielliptic model were naturally suggested and as expected, the three-axis hemielliptic method resulted in better estimation of actual flow rates, even when underestimation still existed. Thus, the three-dimensional reconstruction method could be helpful to refine or adjust current flow convergence methods, especially for asymmetric orifices.

Clinical implications. Utilizing a variety of devices, including intravascular and transesophageal echocardiography, three-dimensional reconstruction techniques have been reported to be potentially important to aid appreciation of anatomic abnormalities, such as mitral valve prolapse, left ventricular aneurysm, complex coronary artery lesions and ventriculoatrial septal defects (23–30,32–34). Color Doppler flow mapping of shunts through septal defects and valvular regurgitant jets was also demonstrated by Belohlavek et al. (31) and Delabays et al. (35). However, these reports did not include quantitative information about color Doppler-imaged regurgitant flow or a comparison of three-dimensionally reconstructed flow images with actual flow rates. Our in vitro study may provide the basis for quantitating and characterizing regurgitant flow events and potentially offer a basis for understanding other flow events, such as shunt flows in various cardiac lesions.

Study limitations. Because the current three-dimensional video composite data used in the present study were obtained from color Doppler flow mapping, limitations inherent in color Doppler flow mapping for imaging the regurgitant jets and flow convergence, such as variability with color gain and wall filter setting, and variability with aliasing velocities, such as observed in the present study, were carried into the three-dimensionally reconstructed flow images. In particular, the color Doppler filter setting of 1,000 Hz with a 5-MHz transmission frequency corresponded to a filtering of some velocities <15.4 cm/s and might have interfered minimally with color coding of the 19-cm/s velocity flow convergence images. Also, the wall-adherent jet was interrogated at more unfavorable angle than the centrally directed jet, as seen in Figure 3. Thus, the reduced volume of the wall jet might have resulted not only from hydraulic causes, but also from this Doppler angle factor. Thus, these inherent color Doppler limitations should be taken into consideration when interpreting Doppler three-dimensional images.

In our in vitro models, the distal jet showed minimal frontal impingement and rounding by the distal chamber wall, with low velocity vortices generated. However, it was unlikely that such distal impingement would alter our conclusions on the effect of the orifice shape on the three-dimensionally reconstructed jet propagation and volumes.

Another limitation of the present study was that the color Doppler regurgitant flow images were transferred into the TomTec three-dimensional computer as video composite gray-scale images. Thus, information originally acquired as autocorrelation solutions to the digital phase shift during sequential interrogation and displayed as velocity values encoded in RGB, or what is commonly called Doppler color-encoded flow mapping, were ultimately compressed into a gray-scale map for computation. In an intermediate step, velocity information was reduced into a unicolor brightness scale for the regurgitant jet and flow convergence images. This represents sacrificing velocity quantitation capabilities while retaining information on the location and shape of flow, and it was important to develop special color Doppler flow maps and optimize instrument settings to obtain, as much as possible, clear and accurate images of regurgitant jets and flow convergence isovelocity surfaces. Despite these compromises, regurgitant jet propagation and the contour of the flow convergence zone were visualized well and could be analyzed quantitatively. In the future, continued development of computer technology and advanced parallel-processing ultrasound equipment is likely to provide real-time volume imaging and direct transfer of encoded velocity signals in digital format as velocity assignments into computers capable of reconstructing three-dimensional quantitative color Doppler flow images. This should substantially enhance the results of these earliest efforts at three-dimensional reconstruction of flow phenomena.

Conclusions. Our study suggests that three-dimensional reconstruction of flow imaged by color Doppler may add spatial information to aid computation of flow events of complex geometry. In that light, it may strengthen existing methods for quantifying regurgitant flows using both regurgitant jet and flow convergence methods. Direct digital acquisition and angle-corrected flow velocity reconstruction would be anticipated to improve our results substantially.

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